Results of the MuCool Expander Flow Tests Performed at the Meson Cryogenic Test Facility

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Abstract

A MuCool Test Area (MTA) is being proposed at Fermilab to test the feasibility of a liquid hydrogen absorber system. In this system, heat absorbed by hydrogen is removed via a heat exchanger with helium supplied by a Tevatron type refrigerator. The main requirement of this heat exchanger is to maintain the liquid hydrogen density fluctuation within the absorber to +/- 2.5%. In order to achieve this, the helium cryogenic system needs to provide 300 W of cooling capacity between 14 and 18 K (150 W for beam and 150 W for static). Furthermore, switchover to a liquefier mode will be required in order to supply LHe to a 4T superconducting solenoid used to test the hydrogen absorber system in a focusing magnetic field. This report summarizes the helium capacity tests performed at the Meson Cryogenic Test Facility (CTF) to verify that these conditions are obtainable.

Introduction

The future Muon Collider and Neutrino Factory will require an ionization cooling system using a series of liquid hydrogen absorbers to reduce the muon beam's transverse emittance. The Muon Collaboration has proposed a preliminary feasibility study at Fermilab to test one liquid hydrogen absorber and associated systems. The first stage will validate the mechanical and thermal design of the hydrogen absorber system with subsequent stages testing components of a cooling cell together under high-powered beam. The proposed MuCool Test Area or MTA will be located in the Linac area and will be connected to an existing Linac beam extraction point capable of extracting protons from the Fermilab Linac.

The MTA facility consists of a hydrogen cryoloop and helium cryogenic plant. The cryoloop contains the absorber, a pump to circulate the hydrogen, a heat exchanger to condense and cool the liquid, a heater to stabilize the hydrogen temperature, and appropriate instrumentation. The cryogenic plant is a modified Tevatron refrigerator based on the Claude cycle.

The main requirement of the He/H_2 heat exchanger is to maintain the temperature difference in the liquid hydrogen within the absorber at 4 K or below. This condition keeps the liquid hydrogen density within +/- 2.5% (a requirement for proper absorber operation). The nominal temperature of the hydrogen is chosen to be 17 K at a pressure of 17.6 psia. Since the freezing and liquefaction points of hydrogen at normal pressure are 13.95 K and 20.27 K, respectively, the 17 K point represents a good median between both extremes. For the specific heat exchanger design, these requirements translate to a helium inlet of 14.0 K, outlet of 18.0 K at a pressure of 16.0 psig and flow rate of 27 g/s. The high flow rate (~27 g/sec) is required in order to keep the ΔT across the He/H_2 heat exchanger to within 4 K for the necessary heat load. The helium system must be capable of providing 300 watts (or more) of cooling at 14 to 18 K (150 W for beam and 150 W for static).

Subsequent tests at the MTA will use the hydrogen absorber in tandem with an RF cavity embedded within a focusing magnetic lattice to test ionization cooling principles. These tests will be performed using a solenoid currently located at Lab G. The solenoid is a 4T superconducting solenoid requiring liquid helium for cooling of the superconducting coil as well as liquid nitrogen for the thermal shield. Tests performed at the Meson CTF will determine if it is feasible to supply 4.5 K helium to the solenoid using the same refrigerator by switching from the 14 K refrigerator mode to liquefier mode. This will enable the use of a single cryogenic plant to fill the solenoid during off hours, while maintaining liquid in the absorber. If it is proven that this method is not practical then other means of supplying 5 K helium would have to be provided such as a second helium refrigerator or by using portable 500 liter commercial dewars. Figure 1 shows the conceptual cryogenic system for the MuCool Test Area.

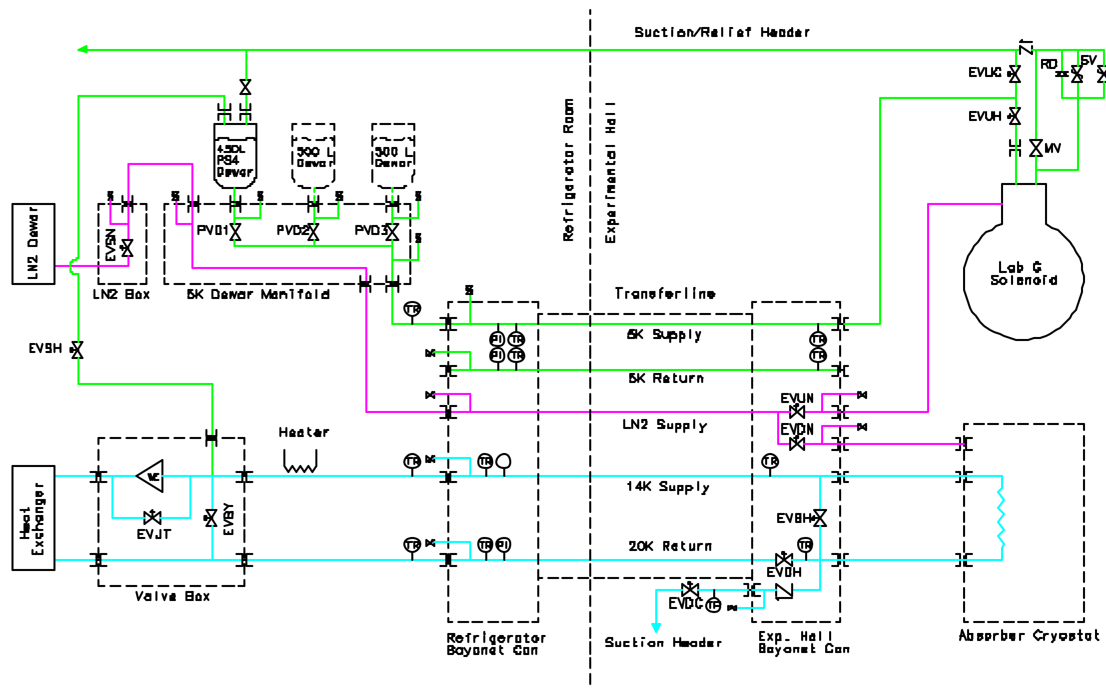


Figure 1: Proposed MTA Helium Flow Layout

The distribution system design is versatile enough to allow automatic switchover to 5 K mode by utilizing the spare single phase bayonet of the valve box while still providing the possibility of using commercial 500 liter dewars through a manifold station.

This report summarizes tests that were performed at the Meson CTF in order to verify that the helium system is capable of providing the necessary cooling. A series of tests were performed to see if the refrigerator can be run in a stable mode for long periods. Heat load tests were performed at different ΔT's. Switchover tests between 14 K and 5 K were also done to determine length of time required to switch modes as well as 5 K liquefaction rate determination.

Experimental Setup

The Meson CTF is an ideal location to perform these MuCool tests because it consists of identical components; cold box, valve box, expansion engines, etc., to those of the future MuCool Test Area (MTA). The MTA will use components taken from the similar PS4 cryogenic system. The Meson CTF consists of three standard Tevatron style refrigerators, each with a "star" type heat exchanger. Each refrigerator is denoted by a color, ie. brown, red and orange. For these tests, only the "brown" refrigerator was used, see figure 2.

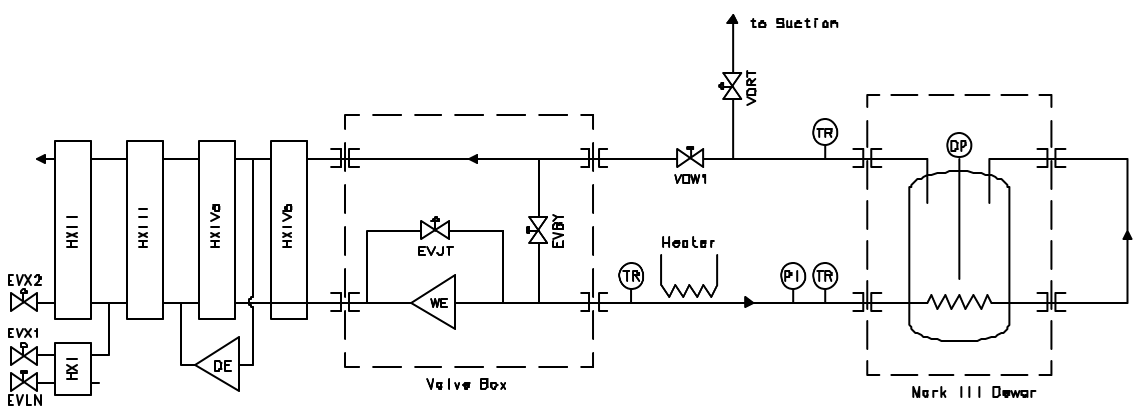


Figure 2: Meson CTF Test Configuration

The 14 K helium was drawn from the refrigerator wet engine exhaust from the valve box through a flexible cryogenic hose containing a 750 W in-line heater. The heater was used to determine the heat load on the refrigerator as well as the flow rate. The heater flow was then directed to the "Mark III" dewar where it entered the high pressure finned tubing circuit and then plumbed into the low pressure dewar inlet of the Mark III. The outlet of the dewar was then connected to the valve box low pressure return line via a flexible cryogenic hose with an in-line throttling "JT" valve. The hose also has a side appendage with it's own in-line valve, which was connected to warm suction and was used as a cooldown line. In order to provide more throughput to achieve the required 27 g/sec, the standard 2 in. wet engine was replaced with a 3 in. engine.

Initial tests utilized a 3 in. dry engine, but it was later replaced by a 2 in. engine. For these tests, the wet engine was locked at or near it's maximum speed in order to maintain the high flow rate requirement of 27 g/sec. The dry engine was allowed to regulate to maintain the wet engine outlet temperature at a constant 14 K. The in-line heater on the outlet of the wet engine was then set to regulate for a fixed ΔT across the heater. The throttling "JT" valve, VDW1, was locked at an appropriate position to achieve a constant wet engine outlet pressure of approximately 16 psig.

Test Results

The first set of tests were done using a 3 in. wet engine and a 3 in. dry engine with no liquid nitrogen flow through the heat exchanger. In this mode the wet engine was locked at about 1740 rpm, which translates to 174.0 rpm on the flywheel and a flow rate of 27.5 g/sec. The dry engine was allowed to regulate to maintain the wet engine outlet temperature at 14.0 K. But even with the dry engine running at a low flywheel speed of 53 rpm, the wet engine outlet temperature could not be raised above 12.5 K when setting the ΔT across the heater for 4.5 K or less. Essentially with the wet engine running at such a high speed and the dry engine on and at a low value, too much refrigeration was being produced. With the dry engine running at 53 rpm on the flywheel, the dry engine inlet temperature stabilized at 145 K.

On this initial test, no attempt was made to run the dry engine any slower. Instead it was decided to replace the 3 in. dry engine with a 2 in. dry engine in order to reduce the throughput of the engine, which would allow it to regulate freely instead of sitting at a low minimum position. Once again in this second round of tests, for ΔT's of 4.5 K and lower, the wet engine outlet temperature stabilized at 13.58 K with the new 2 in. dry engine at a slow flywheel speed of 23.7 rpm. The dry engine inlet temperature for this case stabilized at 181 K. For ΔT's greater than 4.5 K, a wet engine outlet temperature of 14.0 K was achieved and the dry engine began to regulate. It was clear that for ΔT's of 4.5 K and lower with the wet engine producing ~27 g/sec, the dry engine could not be run slow enough to raise the wet engine outlet temperature to 14 K.

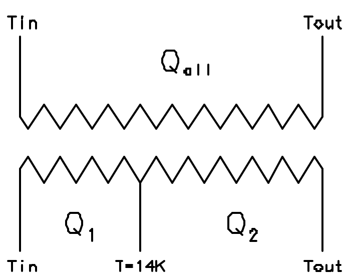
For the third set of tests, the dry engine was turned off and liquid nitrogen flow to the heat exchanger was turned on. Initially the liquid nitrogen flow as controlled from the EVLN valve was set at 20% but was gradually reduced in an attempt to raise the wet engine outlet temperature to the required 14 K. At an EVLN valve position of 5%, the wet engine outlet temperature stabilized at 13.19 K for a ΔT of 4.5 K. Because of the lack of precision and regulation of this valve, no attempt to control the EVLN valve position to values lower than 5% were attempted.

Table 1 shows the tabulated results of all three tests. In the cases where the wet engine outlet temperature did not reach 14.0 K, by knowing the flow rate and the overall heat input, the overall heat load can be separated into two smaller pieces. We can determine the amount of heat required to warm up the wet engine outlet temperature to 14.0 K and separately determine the amount of heat required to warm up from 14.0 K to the final temperature. See Figure 3 for an explanation of the separation of the heat loads. The results indicate that for a 4.0 K ΔT starting at 14.0 K and 25.27 g/sec, the heat load is

551.0 W which is considerably greater than the required 300 W. Figure 4 shows the spread of values for the different ΔT's and configurations in graphical form.

	Wet Engine Flywheel Speed (rpm)	Wet Engine Inlet Temp. (K)	Wet Engine Outlet Temp. (K)	Wet Engine Outlet Press. (psig)	Heater Outlet Temp. (K)	Calculated Flow thru Heater (g/s)	Heat Input (watts)	Dry Engine Flywheel Speed (rpm)	Dry Engine Inlet Temp. (K)
3" Wet Engine and 3" Dry Engine	174.00	21.53	12.49	15.53	17.02	27.54	676.00	53.00	145.30
			12.49		*14.00*	*27.54*	*227.40*	*<--- Calculated Heat Input to Warmup to 14.0 K*	
			14.00		*17.02*	*27.54*	*448.50*	*<--- Calculated Heat Input from 14.0 K to 17.02 K*	
3" Wet Engine and 2" Dry Engine	176.80	23.76	13.58	16.01	18.05	25.27	608.80	23.71	181.30
			13.58		*14.00*	*25.27*	*57.80*	*<--- Calculated Heat Input to Warmup to 14.0 K*	
			14.00		*18.05*	*25.27*	*551.00*	*<--- Calculated Heat Input from 14.0 K to 18.05 K*	
	176.80	24.54	14.00	16.00	19.02	24.91	673.30	33.00	172.50
	176.80	24.65	14.00	15.95	19.35	24.73	710.60	46.20	164.30
3" Wet Engine with Dry Engine off and 5% EVLN Flow	173.70	23.37	13.19	14.57	17.82	25.58	639.00	NA	NA
			13.19		*14.00*	*25.58*	*113.00*	*<--- Calculated Heat Input to Warmup to 14.0 K*	
			14.00		*17.82*	*25.58*	*526.00*	*<--- Calculated Heat Input from 14.0 K to 17.82 K*	

Table 1: Tabulated Expander Test Results



$$Q_{all} = \dot{m}(H_{out} - H_{in})$$

$$Q_{all} = Q_1 + Q_2$$

$$Q_1 = \dot{m}(H_{14K} - H_{in}) \longleftarrow \text{Heat required to warmup to 14K}$$

$$Q_2 = \dot{m}(H_{out} - H_{14K}) \longleftarrow \text{Calculated heat from 14K to Tout}$$

Figure 3: Heat Load Calculation

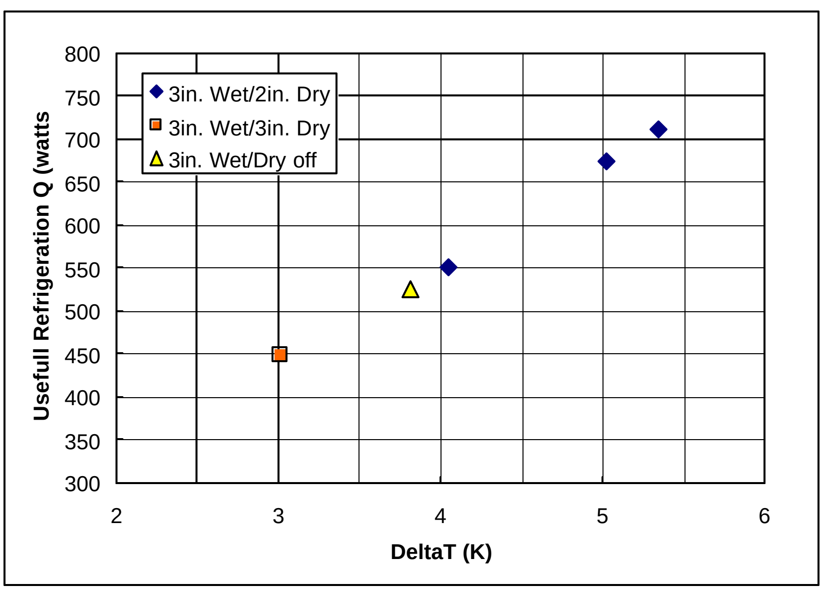


Figure 4: Q versus ΔT (starting from 14.0 K)

A final set of tests were performed to determine the length of time needed to switchover from 14 K to 5 K mode in order to fill the Lab G solenoid. Tests were done in the 3 in. wet engine and 2 in. dry engine configuration. As seen on Figure 5, the results show that it takes approximately (1) hour after the start of nitrogen flow for the nitrogen pot in the heat exchanger to start building liquid and approximately 2.5 hours for the dry engine inlet temperature to drop below 50 K from it's initial 180 K value. Liquid helium does not begin to build until the liquid nitrogen pot has been filled with the liquefaction rate increasing significantly once the dry engine inlet drops below 50 K. At this point the liquefaction rate reached a maximum of approximately 48 liter/hr. Earlier tests done using a 3 in. dry engine yielded a liquefaction rate of 78 liter/hr. For the earlier 3 in. dry engine tests only a liquefaction measurement was taken. No 14 K to 5 K switchover data was collected. Throughout these tests, no attempt was made to fine-tune the refrigerator for the optimal liquefaction rate. It is conceivable that with some amount of tuning, liquefaction rates approaching 100 liter/hr. are possible.

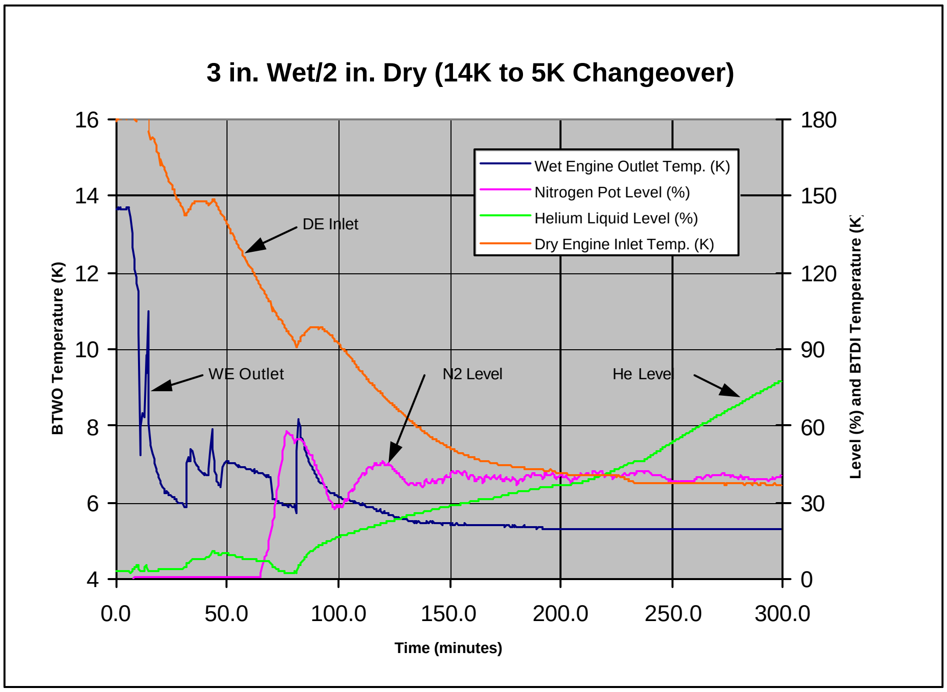


Figure 5: 14K to 5K Switchover (using a 3 in. Wet and 2 in. Dry)

The total amount of liquid needed to fill the Lab G solenoid (300 liters), the PS4 dewar (450 liters) and transfer line (~25 liters) totals 775 liters of helium. If we assume that these vessels are already at 5 K, the amount of time required to fill these vessels with a liquefaction rate of 78 liter/hr would be (775 liter / 78 liter/hr.) or 9.93 hours. If we take into account the 2.5 hours needed to initially cool down the system from 14 K, the total amount of time required would be 12.5 hours. This case assumes that the vessels and transfer line are already at 5 K. If these vessels were initially at room temperature, many more hours would be needed to cool down the system.

There are several ways to speed this process up. One way is to use a 3 in. dry engine instead of a 2 in. version. The 3 in. expander has the advantage of greater throughput and thus can initially cool down the heat exchanger more quickly than the 2 in. machine. It is possible that a 3 in. dry engine could cool down the dry engine inlet temperature in about 1 hour versus the 2.5 hour duration for the 2 in. engine. As was stated before, the 78 liter/hr. liquefaction rate can be improved upon with proper tuning. Values approaching 100 liter/hr. are possible.

Conclusions/Recommendations

The tests performed at the Meson CTF determined that for a 4 K ΔT across the heat exchanger, approximately 550 W of cooling are available and 448 W available for a ΔT of 3 K. Depending on the tests, the wet engine flow rate ranged from 24.73 g/sec to 27.54 g/sec. These flow rates corresponded to a wet engine flywheel speed of about 175 rpm which translates to the maximum motor speed for the given motor to flywheel pulley ratio. These engines are capable of running up to 200 rpm on the flywheel with the proper pulley ratio installed. A change from 175 rpm to 200 rpm would increase the flow by 12.5% approximately. Above 200 rpm, engine performance levels off and the possibility of mechanical wear increases. These tests subjected the wet engine to many days of continuous operation at 175 rpm flywheel speed with no noticeable degradation of performance.

As was discussed earlier, a trim heater on the outlet of the wet engine could be used as a direct way to maintain the 14.0 K inlet to the absorber. The heater would "trim" out any small temperature fluctuations from the helium supply. The dry engine would still be set to regulate for 14.0 K wet engine outlet temperature but because of it's location in the helium system any changes in the dry engine may take several minutes for the results to be seen on the wet engine outlet temperature. Furthermore, as the results show for ΔT's of 4.5 K or smaller, the wet engine outlet temperature does not reach 14.0 K. The "trim" heater can be used to provide that extra amount of heat to reach the 14.0 K point.

One requirement of the absorber system is the need for it to be stable whether beam is On or Off. The sudden loss of beam would be seen on the helium system as an immediate loss of heat load causing the helium return temperature from the absorber to quickly drop. This colder return up the shell side of the heat exchanger would subsequently translate to a colder wet engine exhaust. One way to address this condition would be to use the trim heater. The heater can react to sudden loss of beam or other transients and ramp up accordingly.

Normal operation of the absorber requires that the helium ΔT across the heat exchanger be 4 K or less. With the 14.0 K inlet requirement, this means that the outlet of the heat exchanger would need to be 18.0 K or less. As we have seen previously, these tighter ΔT's mean that the dry engine would run at it's minimum position continuously with the wet engine outlet temperature stabilizing below 14.0 K. By artificially injecting some heat on the helium system, the heat exchanger would warm up, allowing the dry engine to regulate.

As was discussed earlier, a future stage of the Linac MuCool Test Area will require the need of a 5 K helium supply to feed the Lab G solenoid. Tests performed at the Meson CTF determined that the refrigerator is capable of providing a 78 liter/hr. liquefaction rate with a real possibility of increasing this rate with proper tuning. One of the main issues involved in providing liquid helium to the Lab G solenoid is the fact that in most cases there would still be a need to concurrently supply helium to the absorber system to keep the hydrogen loop in a liquid state.

As of this date, it is unclear on the exact planned run mode of the hydrogen absorber tests at MTA. It is important to know if the system will be run continuously for days on end, run only during the day and off in the evenings or run several days consecutively followed by several days of shutdown. The planned run mode will greatly affect the way 5 K helium is supplied to the Lab G solenoid.

Assuming that the hydrogen absorber beam tests are run during the day shift with the remaining hours without beam or perhaps run several days consecutively followed by a day or two of shutdown, the off hours can be used to fill or top off the 5 K system. Because of the complexity and time required to fill the hydrogen cryoloop, it is desirable that during these beam-off hours no attempt will be made to dump the hydrogen from the cryoloop. This would require that enough 14 K flow be sent to the He/H_2 heat exchanger to keep the hydrogen in a liquefied state while also supplying the 5 K system. One way of achieving this is to run the refrigerator in 5 K mode with the bulk of the flow sent to the 450 liter PS4 dewar with the return gas coming back to the valve box/heat exchanger, see Figure 1. A small amount of flow, the minimum required to keep the hydrogen cryoloop liquefied for the given static heat load, would be diverted to the absorber. The "trim" heater on the wet engine exhaust would be used to warm up the 5 K diverted flow to 14 K.

The hydrogen cryoloop heat load during BEAM OFF conditions consists of the cryostat heat leak (24 W), the pump heat leak (26 W), and the pump mechanical work. Due to the large latent heat of hydrogen, required fluid speed to maintain liquid in the loop is less then 2 m/sec. Assuming that the hydrogen pump is capable of running in the 5-10 Hz speed range, the pump mechanical work is negligible compared to the static load. On the other hand, heat capacity of the helium at 14 - 20 K and atmospheric pressure is 32 J/g. Therefore, the helium flow rate to compensate the cryoloop heat load during BEAM OFF conditions is 1.58 g/sec. With a 1.3 heat uncertainty factor it translates to approximately 2 g/sec, which is about 50% of the plant's capacity in the liquefier mode. To prevent hydrogen from freezing in the absorber, the 2 g/sec of liquid helium needs to be warmed up with the trim heater to 14 K.

The rest of the plant's liquid capacity will be used to fill the PS4 dewar at a 35 to 50 liter/hr. rate. Data taken from Lab G during operations of the solenoid show a boiloff rate of approximately 5 liter/hr or 40 liter/shift. If we take this value as the boiloff rate for the entire system, when full, the system can be run for 155 hours or 6.5 days between fills. One possible scenario for filling the liquid helium system is to have an initial bulk fill of the entire system using the refrigerator in liquefier mode or by using 500 liter commercial dewars and then topping off the system on a nightly basis during beam off conditions.